A DYNAMICAL SURVEY OF INNER SOLAR SYSTEM ASTEROIDS: PRELIMINARY RESULTS

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ABSTRACT

Results from a numerical integration survey of all 179 currently-known inner solar system asteroids with $a \le a_{Mars}$, $q \ge a_{Mercury}$ are presented. A surprising number of asteroids are currently in, or very near, mean-motion resonances with Mercury, Venus, Earth, or Mars. Some of the resonance associations are of high order. Most of the resonance associations are relatively short-lived, with the asteroids wandering in and out of resonance on timescales of hundreds to several thousand years.

Key words: celestial mechanics — resonances — asteroids — minor planets

Integrations and analyses were performed with Newton (Murison 1998), a solar system numerical integration computer program that is able to automatically identify mean-motion resonances of any order. Initial conditions for the planets were taken from DE405 (similar to DE403 — Standish 1994, Standish et al. 1995). The integration method used in this study is a variable step size Bulirsch-Stoer, adapted from Press et al. (1992). All planets — Mercury through Neptune — were included in the purely gravitational force calculations. Earth and Moon were treated as one body.

Asteroid initial conditions were obtained from Bowell's list (Bowell 1998). As of 18 September 1998, the list contained 174 asteroids that satisfied the selection criteria $a \le a_{Mars}$, $q \ge a_{Mercury}$. The latter condition was imposed in order to exclude the asteroids that would potentially require general relativistic corrections. Five additional asteroids were taken from recent Minor Planet Center electronic circulars (see MPEC 1998).

Four stages of resonant asteroid filtering were employed. The initial integration was for 500 Earth years. Asteroids that appeared to be in, or could not be considered excluded from, one or more mean-motion resonances with any of the planets Mercury through Saturn were then integrated for 1000 years. Similarly, survivors went on to 3000 years, then to 10,000 years. An asteroid is here considered *not excludable* from a $(p+q):p$ mean-motion resonance if the critical angle does not circulate within the integration time span.

The algorithm employed by Newton does not actually detect libration *per se* of the critical angle, but rather it detects circulation. Possible libration is inferred from a demonstrated lack of circulation over some interval. Hence, the algorithm cannot say for certain whether or not an asteroid is *in* a mean-motion resonance, but it can conclusively tell if an asteroid is *not*.

This algorithm has several useful advantages. First, resonance detection is complete up to a given integer $p_{\max}$. Second, it is very fast. Third, the libration amplitude and the center of libration are byproducts of the resonance detection calculation. Fourth, high-order resonances are found as easily and quickly as low-order resonances. Automated resonance detection leads to a huge time savings. Hence, a large number of asteroids can be tested for mean-motion resonance associations. This new algorithm is described in more detail elsewhere (Murison 1999).

Figures 1 and 2 show the main results of the integrations. The number of asteroids that are not excludable from being in resonance, as a function of integration time, is shown in Fig. 1. The decline is fit well by a power law $N = N_0 t^{\alpha}$ with slope $\alpha = -0.58$ and $N_0 = 5250$. In Fig. 2 (note the ordinate scale change) we have, for each planet separately, the number of mean-motion resonances associated with that planet as a function of

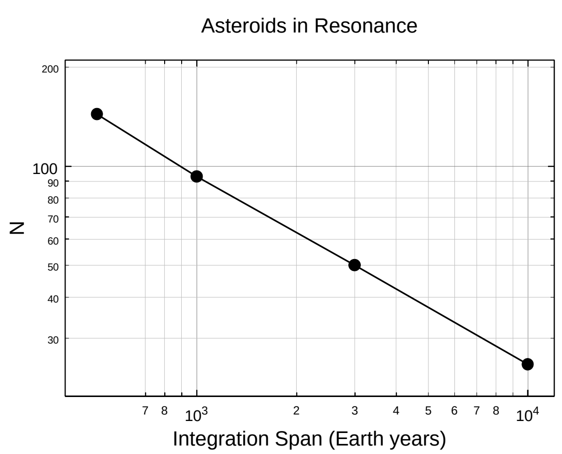

FIG. 1 — Number of asteroids not classifiable as not being in resonance as a function of integration time.

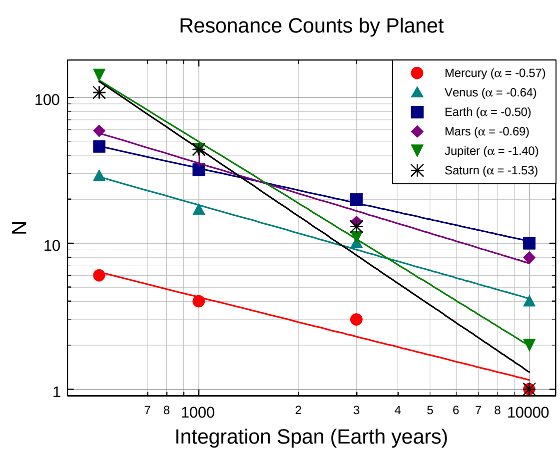

FIG. 2 — Resonance counts per planet as a function of integration time.

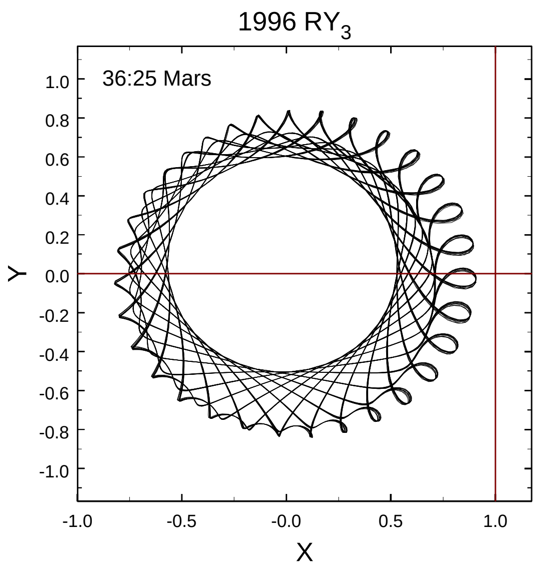

FIG. 3 — 500-year orbit trace of 1996 RY_3 projected onto the rotating xy plane. Mars is fixed at (1,0).

integration time. Again, we see a power law dependence, but with two groupings. Resonance counts associated with the inner planets Mercury through Mars exhibit one behavior, with slopes in the range $-0.7 < \alpha < -0.5$, while those of the two outer planets Jupiter and Saturn behave differently, their slopes being much larger, $\alpha \approx -1.5$. Due to multiple resonances for some asteroids, resulting from "slow drifters" contamination (see below), there appear to be more resonance associations (Fig. 2) than there are asteroids in resonance (Fig. 1). The outer planet grouping turns out to consist almost exclusively of slow drifters. As the integration time increases, more and more of these are shown to be circulating in the critical angle. By t=10,000 yr, all but a few have disappeared. Contamination for the inner planets is much less severe, since the planetary periods are shorter, leading to quicker identification of circulators. It is difficult, for the inner planets, to automatically separate the drifters from asteroids that are actually in and then leave a resonance. One would have to visually inspect $\sigma(t)$ for each asteroid/reference-planet/resonance combination — a daunting endeavor.

Figure 3 shows a 500-year orbit trace of a resonating asteroid projected onto the orbital plane of the reference planet. The coordinate frame rotates and scales with the reference planet, so that the reference planet is fixed at the plot location (1,0). Figure 4 shows the corresponding critical angle for an integration covering a span of 10,000 years.

1996 RY_3 is an example of a "slow drifter". It is very near the 36:25 resonance with Mars, and it is strongly influenced by the close proximity of that resonance, but the critical angle clearly

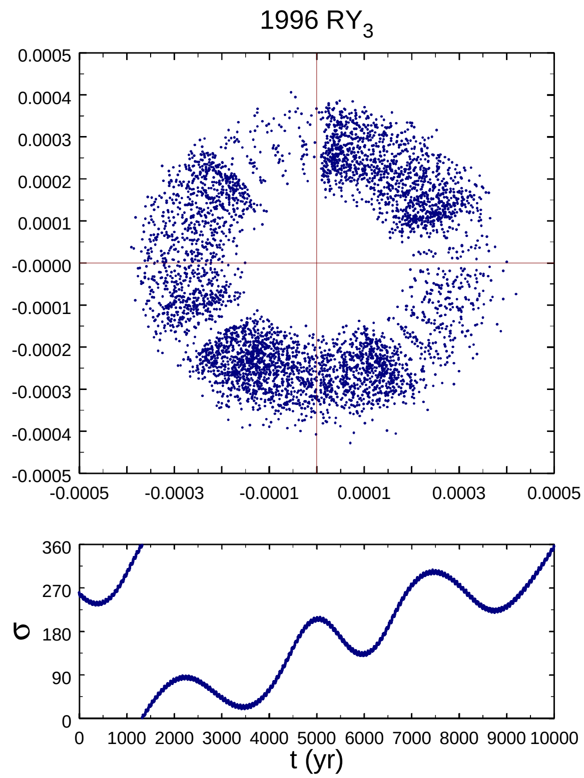

FIG. 4 — The resonance critical angle for 1996 RY_3 for 10,000 years. The radius in the upper panel is $\vec{r} = [(a - a_{\min}) + \frac{1}{2}(a_{\max} - a_{\min})] \cdot \begin{bmatrix} \cos\sigma \\ \sin\sigma \end{bmatrix}$

circulates. Hence 1996 RY_3 is one of the contaminators in the $< 10,000$ year resonance statistics.

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